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Examining Potential Environmental Consequences of Climate Change and Other Driving Forces on the Sustainability of Spanish Olive Groves under a Socio-Ecological Approach

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Abstract: Olive groves form characteristic Mediterranean socio-ecological landscapes, occupying more than 5 M ha; 2.5 M ha in Spain. In recent decades, traditional extensive management of olive groves has shifted to an intensive regime, with some cases of abandonment. These situations triggered negative environmental and economic externalities that led farmers to adopt increasingly multifunctional management models. From a transdisciplinary perspective, the current state of Spanish olive groves was analyzed, assessing their vulnerability to climate change as one of the main threats to their sustainability. Based on our findings and assuming that by 2050, in the Mediterranean, there will be an increase in temperature of 0.8–2.3 °C and a decrease in rainfall of up to 200 mm per year, a displacement of the distribution area of olive groves is expected towards zones of lower temperature and higher moisture. The predicted climatic conditions would increase evapotranspiration of vegetation and atmospheric CO_2 emissions. Moreover, climate change will reduce the chill accumulation in olive groves, altering its flowering, fructification and crop yields. Thus, it is necessary to adopt management models that promote olive grove resilience in face of climate change, ensuring their socio-ecological sustainability.

Keywords: climate change; conservation agriculture; desertification; ecosystem services; multifunctionality; productivity; sustainability; sustainable farming; threats to olive growing

1. Introduction

Olive trees (*Olea europaea*, L. 1753) are perennial, evergreen woody crops closely linked to Mediterranean environments [1,2] (Figure 1).

These crops are adapted to the Mediterranean climate with dry and hot summers, high annual and daily thermal range, and irregular annual and interannual rainfall that varies in quantity [3]. Although traditionally these crops were grown in scattered, low-productivity farming systems, their territorial coverage increased rapidly, mainly for economic and social reasons [1,4]. This gradual process of expansion shaped a cultural heritage of olive growing, which is now deeply rooted in Mediterranean Europe and southern Spain [5].

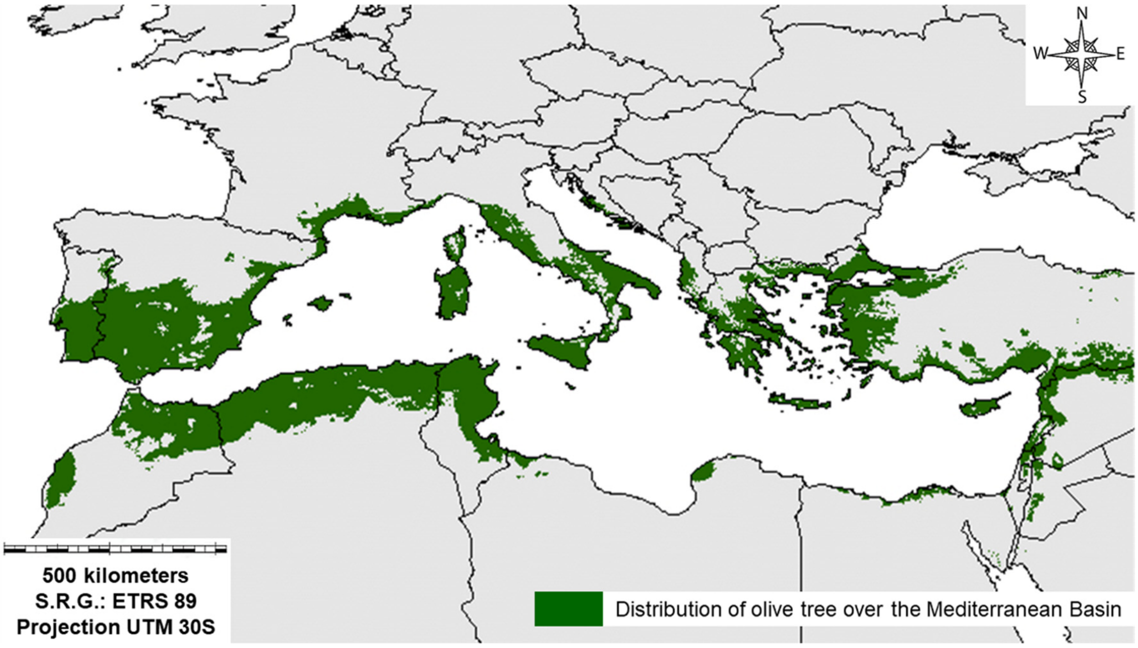

Figure 1. Distribution area of olive trees in Europe.

Spain has the largest area under olive cultivation, with more than 2.5 M ha at present, and is the leading producer of olive oil according to data from the 2017/2018, with an approximate production of 1,298,700 t [6,7]. Italy is the main consumer of olive oil, depending on imports from Spain, Tunisia and Morocco [8], and is the leading exporter of olive oil (Table 1).

Table 1. Olive grove area (hectares, ha), olive oil production (tonnes, t), oil consumption (t) and olive oil export level (t) of the countries with the largest olive grove representation. Average data from 2009–2015 campaigns.

Country	Olive Grove Area	Olive Oil		
		Production	Consumption	Export Level
Spain	2,623,100	1,285,000	528,200	225,000
Tunisia	1,870,000	100,000	33,700	60,000
Italy	1,230,000	450,000	609,600	243,000
Greece	1,125,000	180,000	186,000	13,000
Morocco	1,015,500	100,000	113,500	11,000
Turkey	826,000	220,000	132,100	50,000
Syria	590,000	150,000	140,600	25,000
Portugal	352,000	76,400	78,400	56,000
Algeria	310,000	72,000	59,400	0

In the Mediterranean, the expansion of olive groves led to regional development through promoting employment and curbing rural migration [9]. However, to maintain this type of management, farmers must be ensured of a farm income that will enable them to obtain a decent standard of living and continue farming [10–12]. The olive grove is considered one of the most emblematic woody crops in Spain, especially in its Mediterranean area. There is an important representation of this crop in *Extremadura* and specific regions of *Castilla-La Mancha*, with the greatest crop coverage in the Andalusia region (southern Spain), where it represents 48.63% of national woody crops (1.5 M ha) [13]. Throughout history, this concentration of Andalusian olive groves has shaped the landscape and conditioned the way and quality of life of the population, whose cultural roots in the olive grove are especially well known [1].

Although the fundamental driving force behind the expansion of olive groves has been the progressive demand for olive oil [14], the production of olive groves is currently of great socio-economic importance in terms of employment and contribution to farm income in Spain (i.e., 10% of the sector). However, an analysis of the olive oil value chain shows an imbalance with respect to the production stages of the olive sector, where the low values of bulk oils affect the economic viability of olive farms [15]. This economic condition has led to the vulnerability of olive groves, whose sustainability may be threatened by monetary (i.e., low farm income and market price volatility [15,16]), social (i.e., rural exodus and lack of labor [17]), or environmental factors, where erosion stands out as one of the main threats to olive production [16,18], as well as climate change, which will affect temperature and rainfall by changing olive distribution, production and water requirements to maintain a constant yield [19–21].

Since 1900, the average annual global temperature has increased by 0.3–0.6 °C and accumulated rainfall since the 1950s has decreased 1.32 mm year^{-1} [22]. Taking into account that the optimum conditions for olive growing are based on an average annual temperature between 16–22 °C and annual rainfall of 650 mm, changes in temperature or rainfall due to climate change could represent a major threat to the sustainability of these crops [23]. Although there are numerous deterministic and probabilistic studies (i.e., use of Bayesian networks) that predict significant changes in temperature and rainfall patterns in the Mediterranean, with an increase in the number and strength of extreme weather events (i.e., storms and droughts) [20,21,24], the medium- to long-term consequences of climate change for olive groves is still highly uncertain, with research being fundamental to understanding and mitigating the consequences of this threat. In face of these driving forces threatening the sustainability of olive groves, a review was carried out to establish the current state of these farming systems in face of climate change, with special emphasis on their situation in Spain and in Andalusia region. We also analyzed the potential consequences of the main threats against the multifunctionality of olive groves, with the aim of making management recommendations to maximise the sustainability of these crops.

2. Material and Methods

Data Sources

Data were collected from manuscripts published from 1990 to the present, making an exhaustive revision of the existing literature with the purpose of categorising the references in different sections [25]. For searching scientific references, multiple databases were used, highlighting Web of Science (WOS); Google Scholar; Scopus; and ScienceDirect, including research articles published in both the Science Citation Index Expanded (SCIE) and Social Sciences Citation Index (SSCI) categories. In addition, multiple official and technical reports were consulted from different organizations (i.e., Statistical Spanish Office; International Olive Council; Official Regional Government of Andalusia; State Official Bulletin; and Ministry of Agriculture, Fisheries, Food and Environment, among others).

The main categories/sections that the above-mentioned bibliographic search was carried out were keywords closely related to olive-growing and its main threats to sustainability. These main criteria were: (a) olive groves (i.e., European/Spanish olive groves and their productive level); (b) olive-growing management models (i.e., irrigation/rainfed agriculture); (c) Common Agricultural Policy (i.e., concepts related to policies and schemes of quality protection in olive groves); (d) olive groves as socio-ecological systems (i.e., ecosystem services and olive landscapes); (e) sustainability of olive groves (i.e., multifunctional agriculture and Triple Bottom Line assessment); (f) threats against olive groves (i.e., erosion, pests and pollution); and (g) climate change (i.e., concepts related to chilling requirements of olive groves, CO_2, phenology in olive trees, rainfall and temperature).

The process of bibliographic selection is summarized in Figure 2. A total of 320 research and review articles were identified from the databases consulted (i.e., 166 references from WOS; 56 from Google Scholar; 79 from Scopus; and 19 from ScienceDirect), additionally using 21 technical reports. Duplicate references (n = 67), irrelevant records for the study (n = 89) and those where only the abstract was accessible (n = 12) were excluded. Thus, 173 references were assessed for eligibility.

Fifty-six references were excluded because of their similarities with other studies, avoiding repetition of information (i.e., excluded articles with reasons). Finally, 117 references were included in the present manuscript (including technical reports).

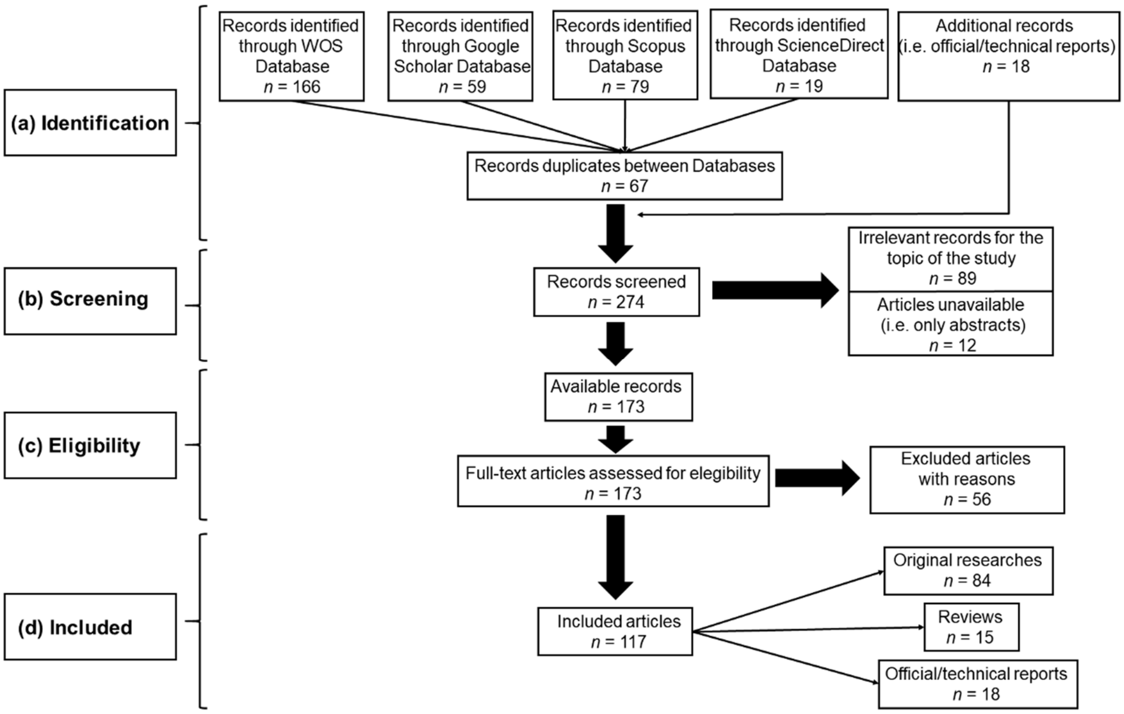

Figure 2. Bibliographic selection methodology including number of articles reviewed in every step (*n*) of each phase: (**a**) identification; (**b**) screening; (**c**) eligibility; and (**d**) included.

3. Results, Analysis and Critical Discussion of the Literature Review on Olive Groves

3.1. Classification of the Main Olive Management Models

Olive groves classification systems can be based on several criteria such as tree density or the use of energy inputs [16,26]. Classifications made by official and technical organisations like the Official Regional Government of Andalusia Bulletin (BOJA) [13] and the Spanish Association of Municipalities of Olive groves (AEMO) [27] quantify agronomic variables that influence olive cultivation. According to these classifications, olive groves can be non-mechanized or mechanized depending to the slope of the area and tree density. Use of machinery is limited in soils with slopes > 20% [1].

Regarding energy inputs, olive groves can be managed in a conventional, integrated or organic way [28]. In these management models, the incorporation of water is allowed, resulting in rainfed or irrigated exploitations. In conventional and integrated olive groves, the use of agrochemicals is possible but, in the second case, it is controlled by standards dictated by specific institutions. Additionally, planting density can be increased, giving rise to crops considered intensive (with or without irrigation) and to highly-intensive crops, always with irrigation [29]. In the organic management, only non-chemical inputs are used [27,30]. Following the criteria of AEMO [27] and Romero-Gámez et al. [31] are attached, in Table 2, the farming characteristics and agricultural practices (including their variations in costs) specific to each management model.

Table 2. Farming practices and management of the olive groves. Units and costs are indicated. *Desvareto* is an agricultural practice related to the removal of stems from the olive tree. *Vareo* is a farming practice entailing hitting the tree with a long stick.

Characteristics and Farming Practices	Non-Mechanized Olive Grove			Mechanized Olive Grove								
	Conventional	Integrated	Organic	Conventional		Integrated		Organic		Intensive		Highly-Intensive
Water regime	Rainfed	Rainfed	Rainfed	Rainfed	Irrigation	Rainfed	Irrigation	Rainfed	Irrigation	Rainfed	Irrigation	Irrigation
Age of olive trees (y)	>25	>25	>25	>25	>25	>25	>25	10–25	10–25	>25	>25	<10
Trees ha^{-1}	80–120	80–120	80–120	100–500	100–500	100–500	100–500	100–500	100–500	200–600	200–600	1000–2000
Pruning (€ ha^{-1})	Biannual	Biannual	Biannual	Biannual	Biannual	Biannual	Biannual	Biannual	Biannual	Biannual	Biannual	Annual
	95.10	95.10	95.10	126.80	126.80	126.80	126.80	46.20	46.20	142.70	142.70	389.60
Waste disposal (€ ha^{-1})	Burning	Burning	Burning	Grinder	Grinder	Grinder	Grinder	Grinder	Grinder	Grinder	Grinder	Grinder
	54.40	54.40	54.40	75.80	75.80	75.80	75.80	26.40	26.40	81.20	81.20	71.00
Desvareto (€ ha^{-1})	Limited	Required	Required	Limited	Limited	Required	Required	Required	Required	Limited	Limited	Not required
	44.00	55.10	42.70	44.00	44.00	55.10	55.10	42.70	42.70	38.50	38.50	0.00
Vegetation cover (€ ha^{-1})	Natural	Natural	Natural	Natural	Natural	Natural	Natural	Live/inert	Live/inert	Natural	Natural	Withdrawn
	279.70	279.70	279.70	279.70	279.70	403.30	403.30	236.90	236.90	394.60	394.60	236.70
Pests (treatments y^{-1} and € ha^{-1})	2	3	3	2	2	3	3	3	3	4	4	5
	165.10	170.30	550.00	165.10	165.10	170.30	170.30	550.00	550,00	216.40	216.40	281.80
Fertilisation (€ ha^{-1})	Foliar and soil	Foliar and soil	Foliar and soil	Foliar and soil	Foliar and soil	Foliar and soil	With irrigation	Foliar and soil	Foliar and soil	Foliar and soil	With irrigation	With irrigation
	70.30	77.60	128.00	70.30	70.30	77.60	77.60	128.00	128.00	110.30	110.30	122.70
Irrigation (m^3 ha^{-1} and € ha^{-1})	0	0	0	0	1500	0	1500	0	1500	0	2000	2000
	0.00	0.00	0.00	0.00	434.00	0.00	434.00	0.00	434.00	0.00	472.00	511.00
Production (kg olives ha^{-1})	1750	1750	1750	3000	6000	3500	6000	3500	5000	5000	10.000	10.000
Collection (€ ha^{-1})	*Vareo*	*Vareo*	*Vareo*	Manual vibrator	Manual vibrator	Manual vibrator	Manual vibrator	Manual vibrator	Manual vibrator	Vibrator/ umbrella	Vibrator/ umbrella	Harvesting machine
	367.00	367.00	367.00	595.00	910.00	595.00	910.00	367.00	367.00	615.00	920.00	810.00

Except for organic management, which was implemented in recent years, all other management approaches have a long tradition and have been applied on older olive groves [13,29]. Pruning is carried out every two years in all management models. *Desvareto* is common in integrated and organic agriculture, particularly due to the presence of trees with several feet. Natural/spontaneous vegetation covers predominate in most management systems, except in organic farming, where live or inert covers are used to mitigate erosion [32]. In highly intensive olive groves, to maximise production and avoid competition for soil nutrients between the olive tree and the herbaceous vegetation, the soil is kept bare (i.e., uncovered) [33]. Regarding to pest treatment and fertilisation, more annual treatments for typical diseases are needed in intensified olive groves, with foliar and soil fertilization predominant in rainfed crops, and fertigation in irrigated crops [34]. The production level of plantations is higher as planting density increases and irrigation is introduced into the system, with harvesting carried out by shaking in non-mechanized olive groves and by vibrator in other types of management. The highest production yields correspond to intensive olive groves with irrigation managed in a highly intensive way [27,33].

In Spain, conventional olive grove management covers the largest area of cultivation [13]. On the other hand, integrated and organic management currently represent just over 15% of the Spanish olive-growing surface, while intensive and high-intensive management makes up 16% [31] (Table 3).

Table 3. Main management models of the olive groves in Spain specifying their water management, area (ha), and representativeness with respect to the total Spanish olive groves (%).

Machinery Use	Management Model	Water Regime	Area	Representativeness
Non-mechanized	Conventional, integrated and organic	Rainfed	728,750	27.50
Mechanized	Conventional	Rainfed	678,400	25.60
		Irrigation	418,700	15.80
	Integrated	Rainfed	161,650	6.10
		Irrigation	174,900	6.60
	Organic	Rainfed	55,650	2.10
		Irrigation	7950	0.30
	Intensive	Rainfed	172,250	6.50
		Irrigation	214,650	8.10
	Highly-intensive	Irrigation	37,100	1.40

3.2. Policies, Certified Quality Systems and Protection Schemes in Olive Groves

There are numerous pieces of legislation that regulate olive production, including the Master Plan for the Andalusian Olive Grove [13] and the Law on Olive Groves in Spain [35]. The policy with the greatest impact and international importance is the Common Agricultural Policy (CAP). The CAP establishes a set of rules and mechanisms for regulating agricultural products to ensure production and guarantee a decent standard of living for rural population. Gradually, the CAP has adapted its objectives to protect the environment by betting on agricultural models that guarantee the proper flow of ecosystem services (ES), considered a contribution of nature to the regional population. Although the CAP entered into force in 1957 with a budget representing 87% of the European Economic Fund and a production target, the McSharry reform (1992) added a direct aid system to farmers [36]. With the "*2000 Agenda*" reform, aid was made dependent on the area cultivated, and the CAP was composed of a first pillar of income support and a second pillar of rural development policies. This latter pillar included payments based on the provision of non-productive ES, with particular emphasis on olive groves as multifunctional agricultural systems [5,37]. With the 2003 reform, decoupled aid came into play, increasing attention to the environment and food security. This measure was adopted in Spain in 2006 [13]. Since its introduction, the CAP has been modified over the decades with the aim of generating productive, competitive and sustainable agricultural systems [38] (Figure 3). In this sense, a transition has taken place from a productivist CAP where the "single payment" was predominant in Pillar 1, to a more environmentally-friendly CAP, where 30% of the budget for direct payments is based on a "greening" regime, referring to the obligations of farmers with arable land to introduce crop rotation and diversification, and to preserve the environment [36].

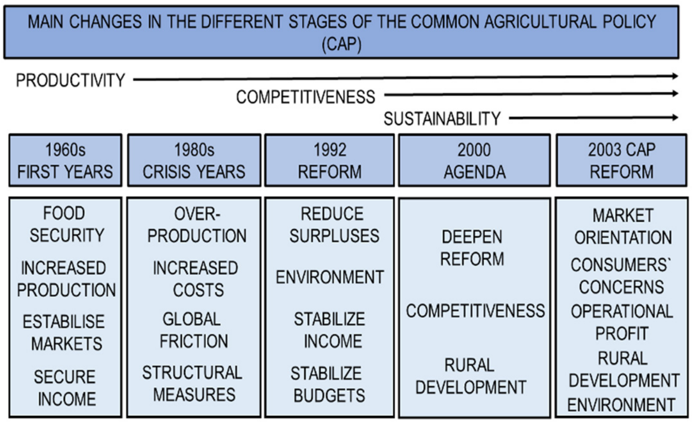

Figure 3. Objectives of each Common Agricultural Policy (CAP) reform, reflecting how the original productivist trend was replaced by competitive agriculture and, ultimately, sustainable agriculture.

3.2.1. Current CAP and Future Trends

The CAP is a policy and legislative framework that conditions and contributes to increasing the economic benefits of the olive grove [11,16]. Currently, with the last CAP reform (2014–2020), the single payment was divided into three pillars, resulting in a more equitable distribution of support, seeking to promote agricultural management models that protect the environment and encourage the recruitment of young farmers [39]. Decoupled aid will thus increase from 10% of the CAP to 12% of its budget, and the single payment, which made up the remaining 88% of aid, will be made up of the following subsidies: (a) basic payment scheme (56%); (b) greening (30%); and (c) payment for young farmers (2%). Thus, the costs of the current CAP will represent 37.8% of the European budget, with its main objectives being to strengthen the agricultural sector in Mediterranean countries, with emphasis on olive cultivation in Spain, where these subsidies are essential to guarantee the economic sustainability of these crops [16,40], and to commit to environmental objectives related to the conservation of biodiversity [41]. Furthermore, the new post-2020 CAP reform presents as a challenge several environmental objectives, highlighting climate change. Thus, post-2020 CAP focus is on promoting a resilient agricultural sector to guarantee food security and minimise the environmental impacts of agriculture [12,39].

3.2.2. Main Protection Figures in Olive Groves

In addition to the policies and regulations mentioned, the relevance of different schemes of quality protection (or quality assurance) of olive groves must be highlighted. These schemes, mainly Protected Designations of Origin (PDOs) and Protected Geographical Indications (PGIs), provide added value and a seal of differentiated quality to the foods produced under their protection. However, while in PDOs the food product must be produced, at all stages, in the defined geographical area, PGIs allow some phase of the food production to take place outside the production area [42]. At a European level, although Italy is second-ranked in terms of olive growing area with more than 1.2 M ha and a production level of 450,000 t of olive oil year^{-1}, it has more quality protection schemes, currently 39 PDOs and 1 PGI [8,43]. On the other hand, Spain, with more than 2.5 M ha of olive groves and a production level of 1,285,000 t of olive oil year^{-1}, has, according to the MAPAMA technical report [44], 29 PDOs for olive oil, 12 of which are located in Andalusia, due to the importance of this crop in the region [13].

In Spain, olive grove landscapes have been proposed by the Government of Andalusia for inclusion on the World Heritage List due to their provision of multiple ES. According to the International Union for Conservation of Nature (IUCN) and the United Nations Educational, Scientific and Cultural Organization (UNESCO), the PDOs *Sierra Mágina*, *Sierra de Segura*, and *Sierra de Cazorla* (Jaén, Andalusia), belong to the Biosphere Reserve of *Sierra Morena*, with 61,177.10 ha considered as Natural Parks as a protection figure [45].

3.3. Agricultural Olive Grove Landscapes as Multifunctional Socio-Ecological Systems

Agrosystems are natural ecosystems that have been modified by humans for food production, generating systems with their own biophysical characteristics. In this sense, the interconnections between agrosystems and natural ecosystems result in the configuration of diverse agricultural landscapes [46]. Although the concept of landscape can be understood as a subjective representation, it also refers to a level of organisation formed by the union of visible components (phenosystem) and non-visible phenomena (cryptosystem), giving rise to different landscapes depending on their characteristics [47]. Landscapes have traditionally been classified as natural or cultural; however, human presence and activities are now assumed to be part of their dynamics. In particular, the process of connectivity in landscapes, understood as the interaction between their structure and the socio-economic dimension, is essential for understanding their functionality [48].

Historically, traditional agricultural landscapes in Europe evolved from mono-agricultural systems to multi-rural systems (i.e., diverse agricultural uses) adapted to the structure and function of the landscape. In this way, a social and ecological co-evolution was established that gave rise to productive work landscapes, with rural cultural landscapes and land uses being adapted to local environmental conditions [49,50]. These types of multi-rural landscapes are the foundation of the multifunctional agriculture approach (MFA), based not only on the supply of agricultural products, but also the environmental and social functions, which are related to environmental protection and the preservation of the socio-economic services of rural areas [5]. Multifunctional agricultural landscapes play a key role in providing products for human well-being, supporting the enhancement of biodiversity of wild species and maintaining ES [51].

In southern Europe, natural resources have traditionally been managed with the aim of achieving a balance between the exploitation of productive systems and their conservation [16,28]. Olive groves are an agricultural example of environmentally friendly management. They are considered to be extremely important agricultural systems in the Mediterranean, representing 5 M ha of the European Usable Agricultural Area (UAA) [52]. In fact, olive groves are considered the main representative agrosystem in the Mediterranean Basin and their economic profitability is closely linked to the subsidies of the Common Agricultural Policy (CAP), which requires the implementation of a mixed economic and ecological strategy to preserve them and promote their long-term maintenance [3]. Therefore, to manage these agricultural systems in a sustainable way, olive groves must be considered as productive agricultural landscapes, taking into account not only the supply of products they provide, but also their social and cultural importance within society (i.e., contribution of ES) [37,51].

The slow transformation of many agricultural landscapes over centuries is considered a co-evolution between natural ecosystems and human rural activities that led to a mutual adaptation among abiotic, biotic and cultural factors. Thus, agricultural landscapes came to be considered complex adaptive socio-ecological systems, which present multi-scalar non-linear interactions with feedback loops between ecological and socio-economic components, together with a high capacity for transformation and adaptation to human activities and the environment in terms of their resilience. From this perspective, the biophysical environment of any system acts as a limiting factor over its production, forming an environmental dimension in addition to the social and economic dimensions for evaluating the viability of agricultural systems [16,37,53].

Although olive groves are subordinate to the socio-economic framework due to the social demand for products and the need to generate benefits, their evaluation must be carried out using complex systems and MFA approaches, studying the geo-environmental system and its ecological functions, as well as the impact and consequences of human development on its resources [54]. According to the criteria of Rescia and Ortega [55], while resilience of olive groves consists of ensuring the flow of ES, their economic function is determined by supply services, their social function by cultural services, and their environmental function by regulating services.

Specifically, olive groves provide supply services through the production of olive oil and olives, with Spain being the top world producer of olive oil [7,8]. Regulation services are provided through the improvement of air quality, the control of erosive processes and as a carbon sequestering agent, contributing to the mitigation of climate change [1,56]. Socio-cultural services are provided through their contribution to the generation of employment, representing 32% of the labor force in the agricultural and livestock sector in Spain [13,57]. Finally, transversal services are provided through olive groves' role as reservoirs of great agro-biodiversity, which are home to 43.5% of Mediterranean plant species and 17% of Andalusian vascular vegetation, and host up to 100 species of phytophagous arthropods and 31 species of wintering and nesting frugivorous birds [45,58,59].

In Andalusia, olive groves form an axis for the development of economic activities and research, in addition to providing extremely important services to society, occupying more than 45% of the Spanish agricultural area, which represents 32% of European olive groves [52]. Ecologically, it is worth noting their high natural value due to the presence of semi-natural vegetation near to the olive trees and its location in areas with diverse land uses [13,30].

3.4. Sustainability of the Olive Groves

Assuming the multifunctionality of olive groves, the assessment of the sustainability of agricultural systems forms a complex paradigm taking into account their multidimensionality. In this sense, the sustainability of agrosystems must be achieved through the approach based on Triple Bottom Line Assessment (i.e., TBL), proposed by Lampridi et al. [53], among others. Such an approach considers the need to analyze the economic, social and environmental dimensions of agricultural systems to study their sustainability. However, while the relevance of these dimensions should be equitable, economic interest often takes precedence over the social and environmental dimensions, as they are the main driving force behind the maintenance of agricultural activity [40,60].

Following the TBL approach, social awareness about the value of the externalities of agriculture calls for a change in agricultural management models towards more environmentally conservative alternatives, favouring maximum use of biomass in agricultural systems and its by-products, assuming circular economy models [61]. To help ensure the sustainability of agriculture, optimal production must be pursued, respecting the social and cultural aspects of the crops (i.e., employment generation, deep-rooted tradition), and ensuring that economic benefits are obtained while mitigating as much as possible the environmental impacts derived from tillage practices and fertilisation [11,37]. There are numerous studies that have analyzed the sustainability of these systems from an ecological and economic point of view following the TBL approach. These have considered the main demands and needs of farmers as the main social actors, of multilevel political decision makers, and practitioners in the olive sector [16,62]. The aim is to ensure the economic viability of the crop while maintaining an optimal level of production that provides a good quality of life for farmers and satisfies the main demands of society for agricultural systems [63].

The sustainability assessment of olive groves is crucial to guarantee a stable production and a correct contribution of ES to society. In the last few years, the vulnerability of these systems was increasing due to their low economic profitability and the volatility of their product prices on the market. As a result, farmers have intensified their farming practices to increase the level of production or, alternatively, they have abandoned their plantations [28]. Both decisions have undesirable consequences. Agricultural intensification is associated with an increase in diffuse terrestrial and atmospheric pollution resulting from the increased use of herbicides and pesticides, an increase in soil erosion processes, and the loss of ES. The lower carbon sequestration capacity and less control of erosion processes due to the poor implementation of vegetation covers are remarkable [26]. On the other hand, rural abandonment alters the regional economic system and increases the rate of environmental degradation associated with a loss of a certain type of biodiversity [16]. Therefore, the sustainability of olive groves must be addressed at the landscape level, taking into account the farming systems and their interactions with nearby and surrounding ecosystems [64]. The study of olive sustainability takes on special importance in the face of an unpredictable future where the sustainability of olive-growing systems is particularly threatened by environmental factors such as climate change. The consequences of climate change are still highly uncertain, having a multidimensional character that will have a negative impact on the economic, social and ecological characteristics of these crops, the analysis of the latter being the main objective of this research [20,65].

3.5. Main Threats to the Sustainability of Olive Groves

Given the multifunctional nature of olive groves, they can be affected at the economic, social or environmental dimensions, with threats that challenge their sustainability [56,66].

From the economic point of view, low farm income is the main threat to olive groves. The assurance of a fair standard of living for farmers is the primary societal demand related to agriculture in Spain. At a European level, the main agricultural concerns are related to achieving optimum food security, with standard of living for farmers ranked third [10,67]. The economic vulnerability of olive groves is one of the main problems conditioning farmers to maintain agricultural activity [68]. In Spain, since 2003, farmers have seen their income decrease by 11.49% [69], with a particularly notable decrease in 2009, as a result of the global financial crisis that took place in 2008. This resulted in losses of up to 49.22%. From that year until 2017, there has been a recovery in farm income of 24.28%, however not yet reaching the same level before the global crisis. Considering the current close relationship between the benefits in olive cultivation with the European subsidies received, it is necessary to promote measures to enhance their non-productive ES by encouraging rural development policies through the second pillar of the CAP [3,5,16,40,70].

Socially, rural exodus and abandonment of agricultural land has caused a loss of traditional ecological knowledge, and has destabilized their regional economy [28]. Since the 1950s, due to the industrialisation process, the rural population declined as a result of migration to urban areas. This phenomenon was particularly remarkable in Europe, resulting in Spain's national rural population declining by 35.2% in 2010. Recent studies conducted by the ONU [71] indicate that this migration trend will continue progressively, posing a serious threat to the sustainability of European agriculture. Measures to promote rural return, such as those adopted by the new CAP (2014–2020), should be promoted to foster social inclusion, poverty reduction and the development of rural areas [39,40].

There are multiple environmental threats that can undermine the sustainability of olive groves. Soil erosion causes a decline in agricultural production, with olive groves being especially vulnerable to erosive processes because of their spatial distribution in areas with high slopes [16,18,40]. Olive groves are Mediterranean crops, where dry periods alternate with intense rainfall in a short length of time, generating large surface runoff and loss of soil and edaphic fertility. Due to the medium-high risk of erosion characteristic of these groves, it is necessary to implement vegetation covers (Figure 4), an agri-environmental practice that has been shown to reduce erosion and loss of materials by up to 75% [72]. Another environmental threat is diffuse pollution derived from the use of chemical fertilisers and pesticides. These agrochemicals affect the quality of olive products (i.e., supply ES) and the biodiversity of these systems, an essential factor for maintaining the flow of regulation ES [73]. In this sense, as an improvement in food quality, the European expansion of organic agriculture takes on special importance, with over 340,000 ha of olive groves currently under this management model, which in turn represents 3.5% of the olive groves in Andalusia region [17,74].

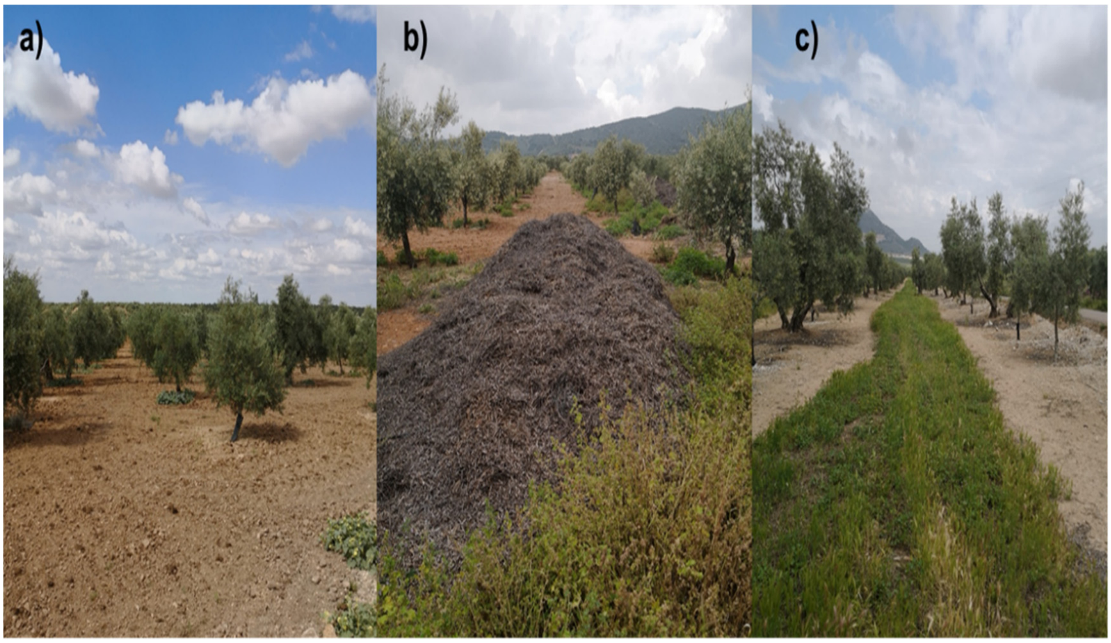

Figure 4. Edaphic management against erosion processes: (**a**) bare soil; (**b**) soil with inert vegetation cover; (**c**) soil with living vegetation cover. Photographs correspond to Protected Designation of Origin (PDO) *Estepa* (Andalusia, Spain).

From an entomological and microbial point of view, it is worth noting the threat produced by the olive fruit fly, *Bactrocera oleae* (Rossi 1790). This diptera of the family *Tephritidae* presents a geographic distribution associated to these crops, affecting its production and quality of the olive [75]. Some measures to control this pest are based on the use of auxiliary parasitoid fauna of the olive fly or the use of preventive mechanisms by the application, on trees, of hydrolyzed proteins and insecticides [76]. Microbiologically, the threat posed by *Verticillium dahliae* (Kleb., 1913), a phytopathogenic edaphic fungus that causes discoloration and winding of olive leaves, leading to the drying of the branches of the tree until its death, stands out [77]. The incidence of this threat has been increased in the last years due to the intensification of olive-growing managements and the development of new plantations on infected soils, being the main treatment against this infection the solarisation of soils and edaphic disinsectation [78]. On the other hand, it must also be highlighted the threat that *Xylella fastidiosa* (Wells et al. 1987) represents, being a generalist phytopathogenic bacterium with special affectation on Mediterranean olive groves whose transmission vectors are insects that feed on the xylem of infected plants [79]. Currently, as measures to address this threat, there are only patterns of eradication that eliminate all host plants and those within 100 metres of infected plants, with prior application of phytosanitary agents [13].

Finally, although climate change is an extremely important threat to the sustainability of agriculture, there is great uncertainty regarding the magnitude of its effects because studies focusing on the impact of climate change, whether deterministic or probabilistic, are based on the use of models and simulations, generating future scenarios [80,81]. The uncertainty regarding the effects of this threat depends on the intrinsic variability of the emission scenarios and climate models used to project future climates, as well as on the impact models used, and the local soil and climate conditions in each ecosystem [82]. However, several studies attest that climate change will generate multiple effects that will affect crop yields, such as a projected decrease in rainfall that will affect water availability, and an increase in temperature that will make crops more susceptible to the pests described above. Additionally, these meteorological modifications can cause a possible shift in the range of olive groves to colder areas due to their chilling requirements, and, considering the tillage practices characteristic of olive groves, the emissions of atmospheric CO_2 will be increased, altering the rate of evapotranspiration of the trees [19,20,83,84].

3.6. Environmental Consequences of Climate Change on Olive Groves

Climate change, defined as the global acceleration of change in the planet's climate due to anthropogenic causes, is the main medium- to long-term threat to agricultural systems, as it has multiple repercussions on agricultural yield and ecological dimensions of these systems [85,86].

Spain will be especially affected by climate change due to its predominant Mediterranean climate, where increased temperature, changes in precipitation, increased drought and increased fire risk will negatively affect the sustainability of agricultural systems [87].

3.6.1. Predictions of the Consequences of Climate Change on Temperature and Rainfall

Within the multiple alterations that will take place due to climate change, the increase in temperatures and the decrease in rainfall demonstrated by multiple researches deserve special attention, being factors that will have several repercussions on olive grove agrosystems [88] (Figure 5). In this sense, Tanasijevic et al. [20] predict, by using climate data from A1B scenario of the Special Report on Emissions Scenarios (SRES) and designing scenarios and spatial simulations to the year 2050, an increase of between 0.8–2.3 °C per year for the Mediterranean region, together with a decrease of up to 200 mm per year in rainfall. However, to better understand the consequences that climate change will have on temperature and rainfall variations, more specific studies are needed. In Spain, Ribalaygua et al. [24] projected a temperature increase of between 2.1–3.75 °C and 1.75–3.1 °C for the maximum and minimum temperatures, respectively. However, authors such as Galán et al. [19] estimate this increase at 4–5 °C over the average temperatures for the Andalusia region by the end of the 21st century. On the other hand, Sumner et al. [65] predicted a 6%–10% drop in rainfall according to projections for the long-term future (100 years) for Spanish Mediterranean region.

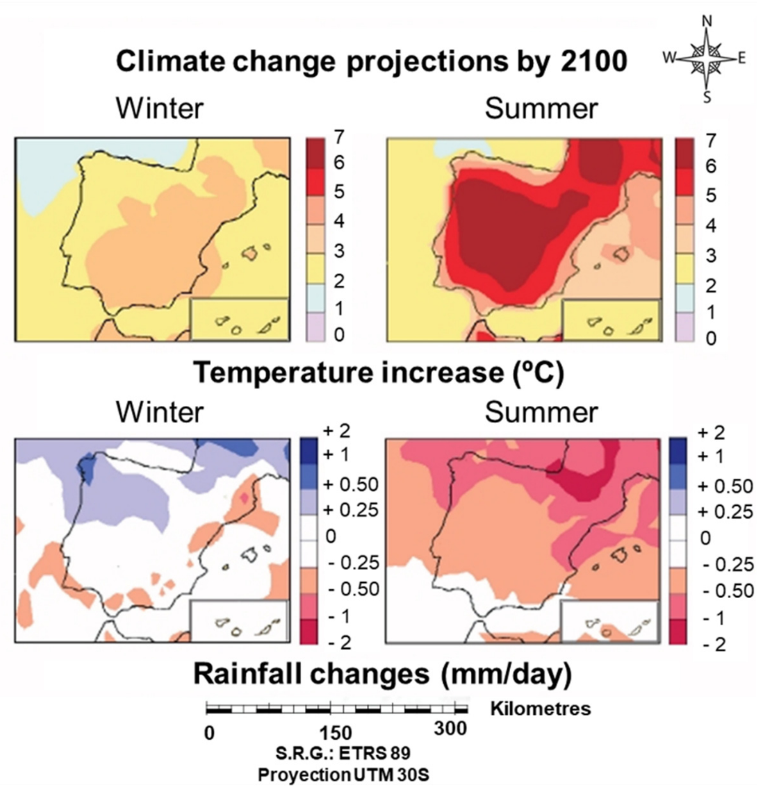

Figure 5. Projections to the year 2100 of the increase in temperature and changes in precipitation in the Iberian Peninsula due to climate change.

Temperature Changes and Impact on Olive Groves

The expected increase in temperature due to climate change will affect the ecology and physiology of olive cultivation. At higher temperatures it is expected a displacement of the potential area of olive groves, increasing its potential distribution area in Spain by 19% [19,86,87,89]. Taking into account that growing olive trees are vulnerable to low temperatures, remaining in a dormant state before producing fruit [90], the increase in temperatures will generate a decrease in winter cold hours between 0–7.2 °C (or chilling units) necessary for the proper development of olive groves and its flowering, which can lead to a drop in agricultural yields [91,92]. Thus, with higher temperatures, a shift to the north and east of the optimal distribution area of the olive trees is expected, due to the lack of fullfilment of chilling hours for both dormancy and vernalization of these trees [91].

According to Rodríguez et al. [84] and Luedeling [93], where predictive models of low uncertainty were used, it was shown that, in simulations to the year 2071–2100, some temperate areas where there are currently olive groves will no longer be suitable for their development. In this sense, authors as Ropero et al. [21] or Benyei et al. [94] have predicted that, because of climate change, there would be a fragmentation of olive cultivation. Specifically, in projections to 2040, the foreseeable increase in average annual temperature due to climate change would fragment the distribution area of olive cultivation in Andalusia, causing a 30% loss of tree cover. Given the hot summers with temperatures above 40 °C, there would therefore be an altitudinal displacement of the olive groves towards mountainous areas, with less frosts and with minimum temperatures that are optimal for the growth of the olive. In the same research, projections to year 2100 showed the progressive nature of the loss of cover and extension of the olive grove in Andalusia, from a tree cover of 40%–50% in year 2040 to a cover of 30%–40% in year 2100.

In addition, the flowering of the olive trees and the ripening of its fruit will be advanced, with phenologies occurring outside the usual dates that will advance the period of olive harvesting [19,86,87,95]. Assuming that maximum temperatures above 35–40 °C affect the proper photosynthesis of the olive trees, abnormally high temperatures will limit the development and growth of the olive, as well as favour the proliferation of pests, since most of them are due to organisms whose life cycles would be shortened and accelerated by high temperatures, increasing the pest population and favouring the emergence of new threats, thus affecting the quality and quantity of the harvest [23].

Rainfall Changes, Evapotranspiration and Water Requirements on Olive Groves

The expected drop in rainfall, although olive trees are quite resistant to drought, is a risk factor for the viability of the olive grove. When annual rainfall is less than 200 mm, production is drastically reduced [21]. In this sense, flowering will be affected by drought conditions, reducing the percentage of fruit production [22]. The concentration of rainfall in the form of storms can increase the magnitude of erosion processes in olive groves, aggravating the degradation of the soil environment and adversely affecting productivity [18,85]. Additionally, the accumulation of large volumes of water in a short time in olive plantations can lead to root asphyxia (i.e., water displaces oxygen in soil, limiting the ability of vegetation to breathe through their roots), affecting the viability of the crop [96].

Due to the combined effect of increased temperatures and drop in rainfall, an increase of up to 9% in crop evapotranspiration is also expected, with the addition of higher quantity of seasonal water being necessary to maintain the yield that olive growing systems currently present [96]. This increased water requirement is highly variable depending on the study area. While several researches have shown the need for a supply of 380–407 mm season^{-1} to maintain agricultural yields in olive groves in southern Spain, specific studies for Andalusia (Spain) estimated values of 397–420 mm season^{-1} [97,98].

Regarding the increased water requirements of olive groves in future projections, the positive effects of the increase in atmospheric CO_2 concentration due to climate change should be taken into account. An increase of CO_2 in atmospheric concentration positively stimulates the photosynthetic process of C_3 plants (i.e., olive trees), promoting plant growth and agricultural yield without increasing water demand by evapotranspiration [99]. From a physiological point of view, a higher concentration of

CO_2 would decrease the stomatal conductance in crops, leading to greater instantaneous transpiration efficiency, and resulting in a reduction of the evapotranspiration of the crop, increasing the water use efficiency. Thus, Hatfield et al. [100] and similar studies showed how in environments where the concentration of CO_2 doubled, plant evapotranspiration could be reduced by 6%–8% in irrigated crops, and by 4% for dry crops, increasing water use efficiency by up to 51%.

3.6.2. Greenhouse Gas (GHG) Emissions and CO_2 Sequestration in Olive Groves

The use of fossil fuels in agricultural activity and the application of nitrogenous fertilisers, generating CO_2 and NO_2 emissions, will also contribute to accelerating the foreseeable changes in temperature and precipitation [33] (Figure 4). Farina et al. [101] estimated that approximately 38.25 t ha^{-1} year^{-1} of CO_2 is emitted from olive groves. However, there is little research evaluating the emission of atmospheric NO_2 from this plantations, being much lower the amount emitted, reaching values of 4.2–6.7 kg ha^{-1} year^{-1} for wet nitrogen (N) depositions, and 10–20 kg ha^{-1} year^{-1} for dry N depositions [102]. The main cause of these emissions is the type of crop management (i.e., mainly irrigation, fertilization, and tillage practices). Thus, intensive tillage practices increase the loss of soil organic matter, reducing its fertility and increasing GHG emissions [103]. Taxidis et al. [104] showed that in management's models such as integrated or organic olive groves, there was a 10.18% reduction in CO_2 emissions compared to conventional management. This is due to the reduction in tillage practices characteristic of these managements and the use of chemical (in a controlled way) or organic fertilizers and waste, characteristics that contribute to reducing CO_2 emissions from soil [103]. In addition, in these agricultural management practices, partial or total plant cover are implemented, contributing to the sequestration of atmospheric CO_2, reducing its concentration [13,63]. Finally, although the application of irrigation is linked to higher GHG emissions, practices such as deficit or drip irrigation could mitigate these emissions by bringing the water directly to the tree roots [105].

On the other hand, olive groves act as carbon dioxide sequestering agents, being one of their most important non-productive ES, being able to capture up to 2.24 ± 2.2 t ha^{-1} year^{-1} in their biomass [29]. However, 80% of carbon sequestration in olive groves occurs at the soil level, where the existence of plant cover plays an important role, storing up to 46.4 ± 20.5 t CO_2 ha^{-1} [13]. In a general way, it is estimated that each olive tree stores, in its first 20 years, an approximate value of 30.89 kg CO_2 year^{-1}. In this way, taking into account the new olive tree plantations in Andalusia between 1990 and 2011 (i.e., 58×10^6 olive trees), there has been a CO_2 fixation of 13×10^6 t, showing an annual carbon capture rate higher to 1.7×10^6 t in the 10th year, representing 3.2% of the total emissions in Andalusia [52]. This character of the olive grove as a carbon sequestering agent constitutes a tool for mitigating climate change through the fixation of CO_2 from the crop itself together with the reduction of emissions due to the energy potential of its by-products, which can be used for the generation of renewable energies such as thermal or electrical energy [13].

3.6.3. Climate Change Mitigation Measures in Olive Groves

Given the threat that climate change poses to agriculture in general and to olive groves in particular, measures should be implemented to curb its impacts. In this regard, it is necessary to promote management models for olive groves that encourage their resilience (i.e., "resilience thinking" approach), and the capacity of these crops to adapt to the climatic conditions that will prevail in the near future in order to ensure the maintenance of the ES that these crops bring to society [106]. From this point of view, it is highly relevant the introduction of new olive varieties more resistant to temperature increases and drought events in order to assure their viability, and the implementation of vegetation covers as a climate change mitigation measure, contributing to the reduction of greenhouse gases, increasing organic matter and soil fertility, and increasing rainwater infiltration and mitigation of erosion processes, generating crops with greater resilience [32,72,107]. Specifically, the increase of soil organic carbon is a key factor in olive groves, since it increases their resilience for adaptation to climate change, contributing to mitigate global warming through atmospheric carbon sequestration [108].

To promote the sustainability of olive groves in face of climate change and help minimising its consequences on weather aspects that will impact on agriculture, it is advisable to consider sustainable conservation tillage options, as no-tillage or reduced tillage, aiming at reducing off-farm inputs such as fuel, and saving costs and labor, while at the same time building up soil fertility [108]. It would be desirable to reduce the use of fossil fuels in farm machinery, as their combustion is the main cause of atmospheric GHG emissions in agriculture (i.e., emissions from agricultural inputs include those from manufacture, and application; and emissions from agriculture machinery include those from production, transportation, and repair of the machinery normalized over the lifetime of the equipment) [109]. Integrated pest control and rational fertilisation methodologies can be implemented where only the indicated products are used based on foliar, soil and water quality analyses, thus reducing the emission of GHG [13,21].

Taking into account the restrictions that climate change will impose on water resources in the near future, and considering that agriculture currently uses about 70% of total water withdrawal for irrigation [110,111], agricultural management models, particularly those applied to olive groves, can opt for implementing rational irrigation techniques on the crops, or maintaining profitable rainfed farms based on agri-environmental management models such as integrated or organic farming (i.e., at present 67.80% of the olive grove area in Spain is managed under rainfed farming conditions [31]). These rainfed farms should be based, in order to increase their profitability, on multifunctional management models such as integrated or organic farming, promoting the implementation of agri-environmental practices, such as the presence of vegetation covers and minimising the use of machinery and labour practices, with the possibility of increasing their benefits by taking advantage of subsidies granted by the second pillar of the CAP in relation to rural development and agricultural conservation measures [5,37]. An example of olive-growing regions that has opted for this strategy can be found in some PDOs in southern Spain, highlighting the PDO *Estepa*, in Seville (Andalusia), where 90% of the integrated olive groves are managed in rainfed regime, with a profitable character in productive and economic terms due to its minimal environmental impacts (i.e., low agricultural abandonment), and the presence of Integrated Production Associations and Groups for Integrated Treatment in Agriculture, being agencies that control and regulate the agricultural practices that are carried out, contributing to take advantage of the maximum yield of these olive farms [13,27,112].

In order to increase the economic and ecological sustainability of olive groves, it would be highly advisable to employ irrigation methods as adaptive measures that maximise water resource efficiency and minimize losses through soil evaporation or percolation [110,113,114]. In this sense, the use of drip irrigation or subsurface drip irrigation (SDI) in olive groves is particularly important, being techniques by which it is possible to apply specific volumes of maximum 1500 m^3 ha^{-1} of water to the crop only in times of water stress. Application of irrigation can be done on the surface of the crop or directly into the soil, respectively, reducing water losses through evaporation [104]. Several studies have shown, with great variability in their results, that these methods forms a localized and efficient systems that reduce net water requirements. In this sense, Chartzoulakis et al. [115] show how drip irrigation reduces water consumption by 30%–70%, resulting in increases of 20%–90% in agricultural yields. However, specific studies conducted in olive groves in Andalusia (Spain) have shown a much smaller reduction in water use, up to 20%, generating an increase in agricultural yield of 13.1% through the implementation of drip irrigation and SDI [114].

On the other hand, regulated deficit irrigation (RDI) consists of a strategy of optimization that purposely stresses the trees at specific developmental stages of the crop such that there is little, if any, negative impact on the yield of marketable product and/or profits [116]. In this sense, the efficiency of the water use is increased and the control of the vegetative growth of the tree and fruit size is improved. The main reasons why a decline in agricultural yield does not occur with this irrigation technique is that plant root growth is favoured by water deficit, and that the high sensitivity of the expansive growth of the aerial parts to water deficits must affect the partitioning of assimilated carbon, as photosynthesis is unaffected by mild water deficits [117]. These strategies are sustainable options for dealing with the water shortages expected to occur in the future due to climate change, since the water deficit allowed increases the optimal use of this resource [105,114,115].

By adopting the measures outlined above, the ecological sustainability of olive grove systems is increased through lowering degradation of the soil environment, resulting in a stable economic return [20,40,83].

4. Conclusions

Olive groves are Mediterranean multifunctional socio-ecological systems whose essential contribution of productive (i.e., supply services) and non-productive (i.e., regulating, cultural and transversal services) ES to society makes them a high conservation priority. Therefore, taking into account the economic vulnerability and low ecological stability of these systems, studies are needed that are aimed at evaluating their sustainability from a landscape perspective, considering the agrosystem and its environment, and valuing the interactions and synergies that take place. In this sense, this research, which has analyzed the main characteristics of olive groves taking into account their main environmental threats, aims to contribute to generate a framework compiling the threats against the sustainability of olive groves, exposing the main measures that can be used to mitigate their effects, maximising the persistence of these agro-systems.

Although there are several threats to the sustainability of olive groves of an economic, social and environmental nature, medium- to long-term climate change is the main threat to the viability of these systems. The changes foreseen in terms of temperature increase and precipitation decrease will have multiple impacts that will affect the potential distribution area of the olive grove and its phenological cycle. Moreover, these consequences of climate change will result in alterations in crop evapotranspiration. From a physiological point of view, an increase in temperature would generate an increase in the evapotranspiration in irrigation systems, increasing agricultural yields. On the other hand, under rainfed conditions, the increase in temperatures along with the drop in rainfall, would reduce plant transpiration, by restricting olive production due to longer drought periods.

In face of this multidimensional threat, the application of agri-environmental practices in olive farming that contribute to the carbon sequestration capacity of these systems (i.e., implementation of vegetation covers) and reduce the emission of greenhouse gases and pollutants responsible for diffuse pollution becomes particularly important. Finally, given the restrictions that will take place on water resources due to climate change, it is necessary to maintain profitable rainfed farms, or increase water resource efficiency and encourage management models that promote the use of non-intensive irrigation practices, such as drip irrigation, SDI or RDI, thus maximising the sustainability of olive groves and guaranteeing the stable supply of their ES.

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